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FINAL REPORT

OFFICE OF NAVAL RESEARCH

N00014-89-J-1029

EVOLUTION OF OVERLAPPING SPREADING CENTERS:
A SEAMARC II INVESTIGATION

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June 7, 1990

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Evolution of Overlapping Spreading Centers: A SeaMARC II Investigation

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During a major SeaMARC II expedition in May-June 1987 we mapped all the overlapping spreading centers (OSCs) north of the equator, between 8° and 18°N, and all their related off-axis scars. With this areal coverage of sidescan sonar and bathymetric data we can document the current status and the evolutionary path of these discordant zones over the last one million years.

The collection of this continuous coverage high resolution sonar data allows us to characterize zones of normal and anomalous bottom roughness, which can be related to the near-axis geological processes which created them.

The major results are discussed in the Macdonald and Fox Scientific American publication (attached), which includes several color plates, and presents a fourth-order model to describe the origin and evolution of ridge axis discontinuities.

We have completed the following tasks: (1) complete analysis of tectonic and magnetic data for the 11°45'N survey (11°20'N to 12°30'N); (2) the nature of faulting on mid-ocean ridges based primarily on SeaMARC II data from our ONR cruise, (3) creation of final 50 m contour interval maps for 8°-18°N merging SeaMARC II data with existing Sea Beam data.

Efforts in the last twelve months have produced:

1) Bathymetric, magnetic and sidescan sonar data from a June 1987 SeaMARC II (SMII) cruise aboard the R/V Moana Wave have been combined with additional data to produce maps of a 140 km by 154 km area centered on the overlapping spreading center pair (OSC) located at 11°45'N on the East Pacific Rise (EPR). These maps include gridded bathymetry and magnetic field anomalies, a sidescan sonar mosaic and a fault map. The bathymetry and anomaly grids were used as inputs in a three-dimensional Fourier inversion resulting in a crustal rock magnetization distribution solution (Fig. 1). These maps have been correlated and interpreted in order to determine the recent (<1 my) history of the discontinuity. The most prominent feature of all five maps is a roughly v-shaped anomalous zone centered on the OSC. The zone is characterized by a positive depth anomaly, a negative magnetic field anomaly within the central (positive) anomaly and a zone of high magnetization in the inversion solution. An anomalous texture and sparse, curved faults mark the zone in the sidescan mosaic and fault map. The shape of this zone indicates a short period of northward migration of the discontinuity .72-.6 may followed by southward migration for the past .6 my. The anomalous zone is not well defined beyond the edge of the central anomaly and this marker is straight and continuous, indicating that if this discontinuity of the EPR existed .72 mya, it's offset was negligible. The present day axis has an orientation of 349°, the edge of the central anomaly has an orientation of 353°, and Jaramillo-age crust to the east of the EPR has an orientation of 353°-355°. This variation in magnetic lineation directions suggests a 4°-6° counter-clockwise change in the direction of spreading in the past 1 my which seems to have been accommodated by asymmetric spreading. Variations in mean fault trend with age are consistent with a counter-clockwise change in the direction of spreading for the same time period.

2) A marked variation in fault-facing direction with spreading rate is observed on the flanks of mid-ocean ridges. On slow and intermediate rate spreading centers, inward facing faults predominate while at fast spreading centers large number of both inward and outward facing faults are observed. The distribution and character of inward and outward dipping faults derived from SeaMARC II data from the flanks of the East Pacific Rise and Galapagos spreading center are compared with observations from previously published data. We suggest that the fault-facing direction variation observed may reflect relative differences in the amount of work required to break the oceanic lithosphere along inward versus outward facing faults at different spreading rates (Fig. 2). For example, due to the thermal structure of a slow-spreading ridge, a fault dipping away from the axis must cut a greater thickness of lithosphere than one dipping toward the axis, thus favoring the occurrence of inward dipping faults. On a fast spreading ridge, the difference in fault length is far less, hence both inward and outward facing faults are likely to occur.

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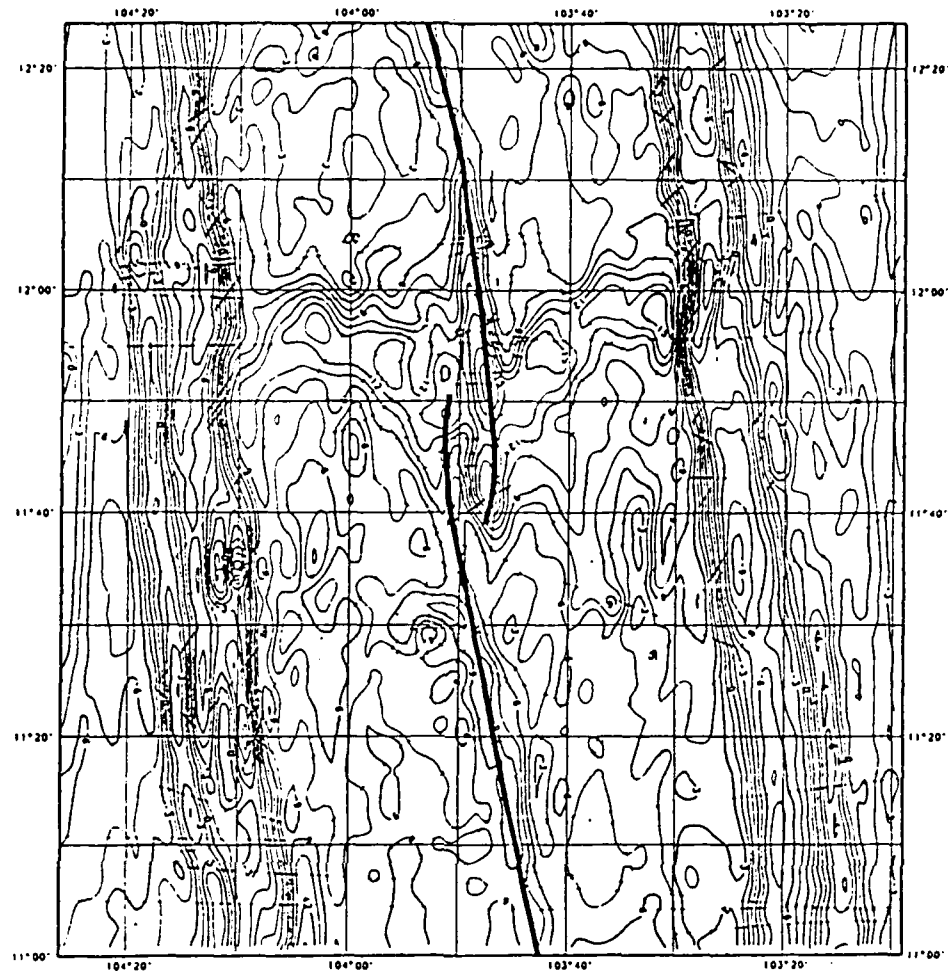
Figure 1. Inversion solution (from 1 km grid) as described in text. The contour interval is 1.5 A/m and ticks on contour lines show track coverage.
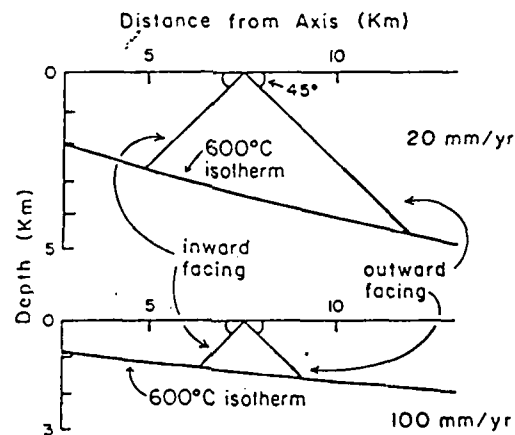

Figure 2. The relative difference in the length of an outward and inward facing fault inclined at 45°, at slow and fast spreading rates. Given these differences in fault length, at slow spreading rates we expect it will require significantly more work to break lithosphere along an outward facing fault than inward facing; hence predominance of inward facing faults. At faster rates, however, the difference in length of inward compared with outward facing faults diminishes and both fault sets are common.

The Mid-Ocean Ridge

It is the longest mountain chain, the most active volcanic area and until recently the least accessible region on the earth. New maps reveal striking details of how segments of the Ridge form and evolve

by Kenneth C. Macdonald and Paul J. Fox

On July 8, 1982, we boarded the research vessel *Thomas Washington* to survey the East Pacific Rise, a volcanic mountain chain that lies under the Pacific Ocean. The Rise is part of the 75,000-kilometer-long formation known as the Mid-Ocean Ridge. Like the seam of a baseball, the Ridge winds around the globe from the Arctic Ocean to the Atlantic Ocean, around Africa, Asia and Australia, under the Pacific Ocean and to the west coast of North America. Even though the Ridge is by far the longest structure on the earth, less was known about its features than about the craters on the dark side of the moon.

Our colleagues from the Scripps Institution of Oceanography had recently equipped the *Thomas Washington* with a new type of sonar system, made by the General Instrument Corporation. Called SeaBeam, it could map a two-kilometer swath of the ocean floor in a single ping of the sonar. It would, we hoped, reveal the ocean floor in unprecedented detail, providing new insights into the forces that form and shape the Mid-Ocean Ridge.

After cruising southeast 2,500 kilometers from the Scripps marine facility

KENNETH C. MACDONALD and PAUL J. FOX have collaborated on many expeditions to the East Pacific Rise and the Mid-Atlantic Ridge. Macdonald is professor of marine geophysics at the University of California, Santa Barbara. In 1975 he received his Ph.D. in marine geophysics from the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution. Macdonald is drawn to the sea by his research, wind surfing and his wife, marine geologist Rachel M. Haymon. Fox is professor of oceanography at the University of Rhode Island. In 1972 he earned his Ph.D. in marine geophysics from Columbia University. When Fox and Macdonald are not cruising the seven seas, they wade in secluded mountain streams, where they try to catch unsuspecting trout with a well-presented fly.

in San Diego, we intersected the crest of the East Pacific Rise, located at a depth of about 2.5 kilometers. The Rise marks the boundary between the Pacific and Cocos tectonic plates, each a slab of the earth's crust and upper mantle. The plates separate at a rate of about 120 millimeters per year (twice the rate at which a fingernail grows). As the plates move apart, cracks form along the crest of the rise, allowing molten rock to seep up from the mantle. Some of the molten rock overflows onto the ocean floor in tremendous eruptions. The magma then solidifies to form many square kilometers of new oceanic crust each year. Only a few kilometers above this activity, we felt like Lilliputians crawling along the spine of a slumbering giant that might awaken at any time.

As the SeaBeam probed the spine of this giant, we watched images of the seascape appear on monitors on board the *Thomas Washington*. We saw some familiar features: the elevated terrain that defines the axis of the ridge and large breaks, called transform faults, that offset ridge segments by hundreds of kilometers. Yet we and Peter F. Lonsdale of Scripps also observed several unknown structures: segments that bend, ridges that overlap and oceanic crust that is warped and distorted near these features.

Since the early 1980's our colleagues in France, the U.K. and the U.S. have also surveyed many stretches of the East Pacific Rise as well as other parts of the Mid-Ocean Ridge. These efforts have revealed that the Ridge has many lateral discontinuities that partition its axis into segments. Although discontinuities differ in form and behavior, most of them are deeper and less active volcanically than the segments they define. As a result, the crest of the Ridge undulates up and down by hundreds of meters over distances of from 10 to 1,000 kilometers. During the past several years we have come to understand how these discontinuities and

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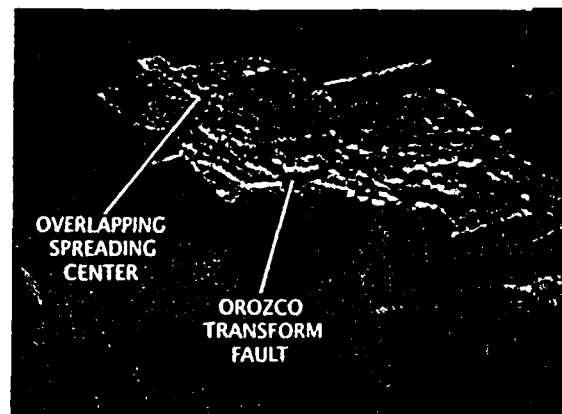
segments evolve and how they are related to processes deep in the earth's crust and mantle.

Sea-Floor Spreading

American oceanographer Bruce C. Heezen aptly described the Mid-Ocean Ridge as "the wound that never heals." In 1956 he and W. Maurice Ewing noticed that the earthquakes in the ocean basin define a continuous belt encircling the world. Because the belt coincided with portions of the Mid-Ocean Ridge that were known at the time, they proposed that the earth was girdled by a continuous system of ocean ridges. Ever since their discovery oceanographers and geologists have tried to get a closer look at the Mid-Ocean Ridge to understand its origins.

The global geologic processes that form and shape the Ridge were not understood until 1960 when Harry H. Hess of Princeton University introduced the concept of sea-floor spreading. Other workers further refined and developed his idea into the theory of plate tectonics. The theory posits that the crust and upper mantle are divided into a few dozen plates, such as the Pacific and the Cocos, which can move with respect to one another. If two plates separate, material from the man-

tle can well up, forming a ridge and new oceanic crust.

The theory of plate tectonics accounts for the largest structures of the Mid-Ocean Ridge. Yet as early as 1960 H. William Menard of Scripps and Heezen discovered that the Mid-Ocean Ridge is a discontinuous structure. As they mapped the Ridge with sounding devices, they found several places where it was offset at right angles to its length. In 1965 J. Tuzo Wilson of the University of Toronto identified these di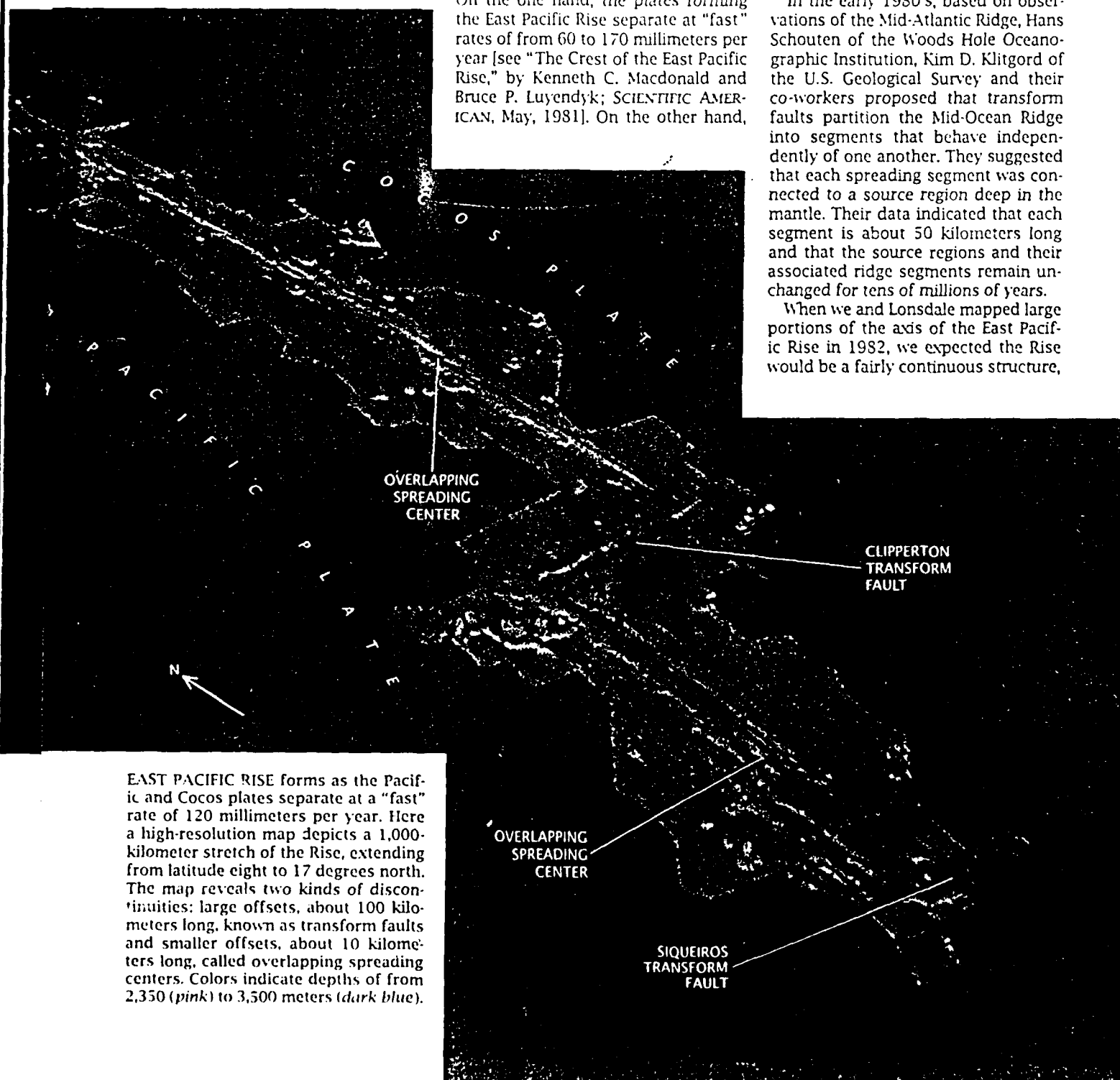scontinuities as transform faults: a boundary formed perpendicular to the length of the ridge, where the edges of tectonic plates slide past each other in opposite directions. Later Richard N. Hey of the University of Hawaii realized the segments defined by two transform faults could shift in a direction parallel to the length of the ridge. This type of discontinuity was called a propagating rift.

By the 1980's oceanographers had identified many transform faults and propagating rifts. They had also determined that different parts of the Mid-Ocean Ridge evolved at different rates. On the one hand, the plates forming the East Pacific Rise separate at "fast" rates of from 60 to 170 millimeters per year [see "The Crest of the East Pacific Rise," by Kenneth C. Macdonald and Bruce P. Luyendyk; SCIENTIFIC AMERICAN, May, 1981]. On the other hand, the plates forming the Mid-Atlantic Ridge are pulled apart at slower rates of about 30 millimeters per year. Because of variations in spreading rates and the rate at which magma is supplied to ridges, the topography of fast-spreading ridges differs from that of slow-spreading ones. The crest of a fast-spreading ridge is defined by an elevation of the oceanic crust several hundred meters high and five to 20 kilometers wide. In contrast, the axis of a slow-spreading ridge is characterized by a rift valley a few kilometers deep and about 20 to 30 kilometers wide.

In the early 1980's, based on observations of the Mid-Atlantic Ridge, Hans Schouten of the Woods Hole Oceanographic Institution, Kim D. Klitgord of the U.S. Geological Survey and their co-workers proposed that transform faults partition the Mid-Ocean Ridge into segments that behave independently of one another. They suggested that each spreading segment was connected to a source region deep in the mantle. Their data indicated that each segment is about 50 kilometers long and that the source regions and their associated ridge segments remain unchanged for tens of millions of years.

When we and Lonsdale mapped large portions of the axis of the East Pacific Rise in 1982, we expected the Rise would be a fairly continuous structure,

COCOS PLATE

PACIFIC PLATE

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EAST PACIFIC RISE forms as the Pacific and Cocos plates separate at a "fast" rate of 120 millimeters per year. Here a high-resolution map depicts a 1,000-kilometer stretch of the Rise, extending from latitude eight to 17 degrees north. The map reveals two kinds of discontinuities: large offsets, about 100 kilometers long, known as transform faults and smaller offsets, about 10 kilometers long, called overlapping spreading centers. Colors indicate depths of from 2,350 (pink) to 3,500 meters (dark blue).

because only nine widely spaced trans-form faults had been discovered along its 5,000-kilometer length. To our surprise, the axis of the Rise was frequently disrupted by many small offsets (more than 40 have been mapped to date). These discontinuities partitioned the Ridge into segments ranging in length from 10 to 200 kilometers. Unlike transform faults, these offsets were characterized by overlapping ridge tips, and they did not have a clearly defined fault that connected the tips [see illustration below]. Since their discovery we have mapped the off-axis regions around these overlapping offsets and have learned that the features evolve rapidly. In addition, we have found that the discontinuities can migrate along the Ridge, at varying speeds and in various directions. Individual segments bounded by those discontinuities can apparently lengthen or shorten. High-resolution maps have also documented similar nonrigid discontinuities on the slow-spreading Mid-Atlantic Ridge.

Magma-Supply Model

To determine the origin of these discontinuities, we and our colleagues attempted to find connections between segmentation and volcanic activity. Although volcanism can change greatly from one segment to the next, it does vary systematically along the length of each segment. The least active regions are deep discontinuities, whereas the most active regions are shallow centers of segments [see "The Oceanic Crust," by Jean Francheteau; SCIENTIFIC AMERICAN, September, 1983].

From these observations and others, we, Schouten and our colleagues developed a magma-supply model of ridge segmentation. In the mantle at a depth of from 30 to 60 kilometers, rocks are heated to high temperatures, but because they are usually subjected to high pressure, they remain in a solid state. The environment is somewhat different at the boundary between tectonic plates. As plates separate, some of the rock decompresses and melts. The molten rock then percolates up through the mantle and fills a shallow chamber in the crust beneath the crest of the ridge. As the chamber swells with magma and begins to expand, the crest of the ridge can be pushed upward by the buoyant forces from both the molten rock in the magma chamber and the broader region of hot rock in the upper mantle [see illustration on page 76].

According to the magma-supply model of segmentation, the greater the supply of molten and hot rock to a region, the higher the overlying ridge segment will be elevated. Furthermore, the rate and volume of the molten rock supply can change from region to region, creating variations in the morphology of the different overlying segments.

The magma-supply model also accounts for smaller structural variations. As magma in the chambers migrates laterally along the ridge axis, the thin, brittle crust above the magma chamber stretches and fractures. The magma can erupt through these fractures to the ocean floor. As the cracks
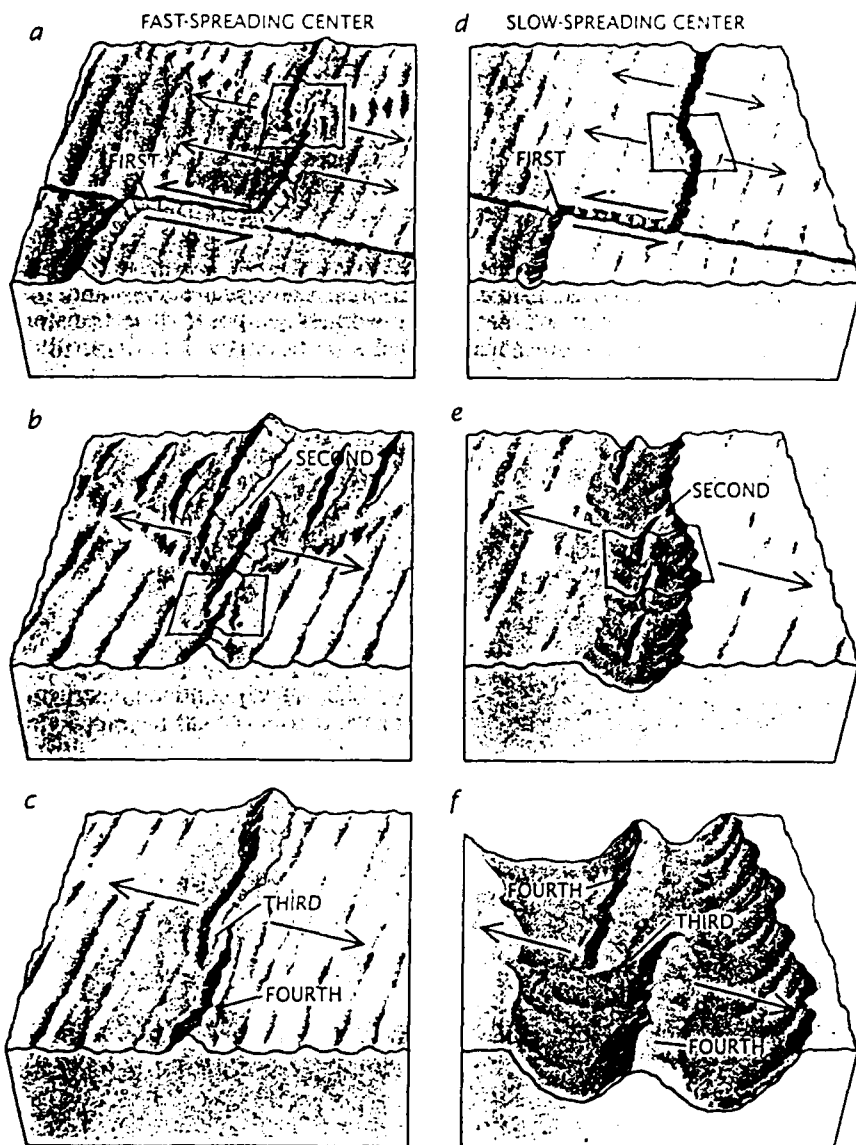
DISCONTINUITIES in the Mid-Ocean Ridge can be classified according to shape, size and longevity. For a fast-spreading center, such as the East Pacific Rise, a first-order discontinuity (a) is a transform fault, where rigid plates slide past each other. It offsets the ridge by at least 50 kilometers. A second-order discontinuity (b) is usually a large overlapping spreading center that offsets the ridge by at least two kilometers. A third-order discontinuity (c) is a small overlapping spreading center that offsets the ridge by .5 to two kilometers. A fourth-order discontinuity (c) is characterized by slight deviations in axial linearity. For a slow-spreading center, such as the Mid-Atlantic Ridge, a first-order discontinuity (d) is also typically a transform fault, but it represents a break in a rift valley rather than a ridge crest. A second-order discontinuity (e) is a bend, or jog, in the rift valley. A third-order discontinuity (f) is a gap between chains of volcanoes, whereas a fourth-order discontinuity (f) is a small gap within a chain of volcanoes. First- and second-order structures are usually flanked by distorted crust that formed as the discontinuity evolved. They are known to persist longer than third- and fourth-order discontinuities, because the oceanic crust near the higher-order structures does not show evidence of distortion.

continue to grow, volcanic eruptions follow in their wake. The eruptions will continue until the production of magma subsides and the supply of magma is exhausted. Temporal variations in melt delivery affect a segment's evolution: when a segment is well supplied with molten rock as compared with its neighbors, the segment tends to lengthen, and when it is poorly supplied, the segment shortens. It is this swelling and shrinking of the magma-supply system, in response to plate separation, that initiates the lengthening or shortening of segments and the migration of small discontinuities.

The magma-supply model appears to agree with seismic and gravitational measurements of the East Pacific Rise. Seismic measurements reveal that a good reflector of sound energy exists about 1.2 to 2.5 kilometers beneath the shallow portions of each ridge segment. This reflector often deepens and then disappears near discontinuities. In 1987 Robert S. Detrick of the University of Rhode Island and his co-workers proposed that the reflector is the roof of a magma chamber. The strength of sound reflection can be explained by a thin cap of nearly 100 percent melt along the top of the chamber.

Most geologists and oceanographers now agree the reflector is a long, shallow body of magma beneath the ridge surrounded by hot rock. John A. Orcutt of Scripps and his colleagues have made seismic measurements along the northern East Pacific Rise, which suggest such a chamber of molten rock is only two to four kilometers wide and less than one kilometer thick. The magma chamber is surrounded by a wider region of very hot (perhaps slightly molten) rock. The reservoir may be six to 10 kilometers wide and three to six kilometers thick. This region of hot rock extends at least to the base of the oceanic crust and probably a few kilometers into the upper mantle [see illustration on page 79].

The presence of magma chambers and hot-rock reservoirs has been supported by precise measurements of the gravitational field there, which indicate the presence of a buoyant mass beneath the ridge axis. From both seismic and gravitational measurements, workers have deduced that the magma chamber resembles a mushroom in cross section: it has a narrow stalk of partial melt feeding a wide but very thin lens of pure melt.

Seismic evidence has not definitively proved that magma chambers exist beneath slow-spreading formations such as the Mid-Atlantic Ridge. Other measurements, however, seem to support a magma-supply model for slow-spreading ridges. Donald W. Forsyth and Ban-Yuen Kuo of Brown University and Jian Lin and G. Michael Purdy of Woods Hole found anomalies in the gravitational field, which were centered over the shallowest portions of several segments of the Mid-Atlantic Ridge. The best explanation for these anomalies is an upwelling of hot mantle material or a thickening of the oceanic crust beneath the shallow portions of each segment. Both interpretations are consistent with the magma-supply model.

It was a great relief that the seismic and gravitational measurements supported, at least in a general sense, the magma-supply model of segmentation. We and many other tectonicists and geochemists had stuck our necks out fairly far with that hypothesis. True, some of us thought the chamber would

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RIFT VALLEY

SECOND-ORDER DISCONTINUITY
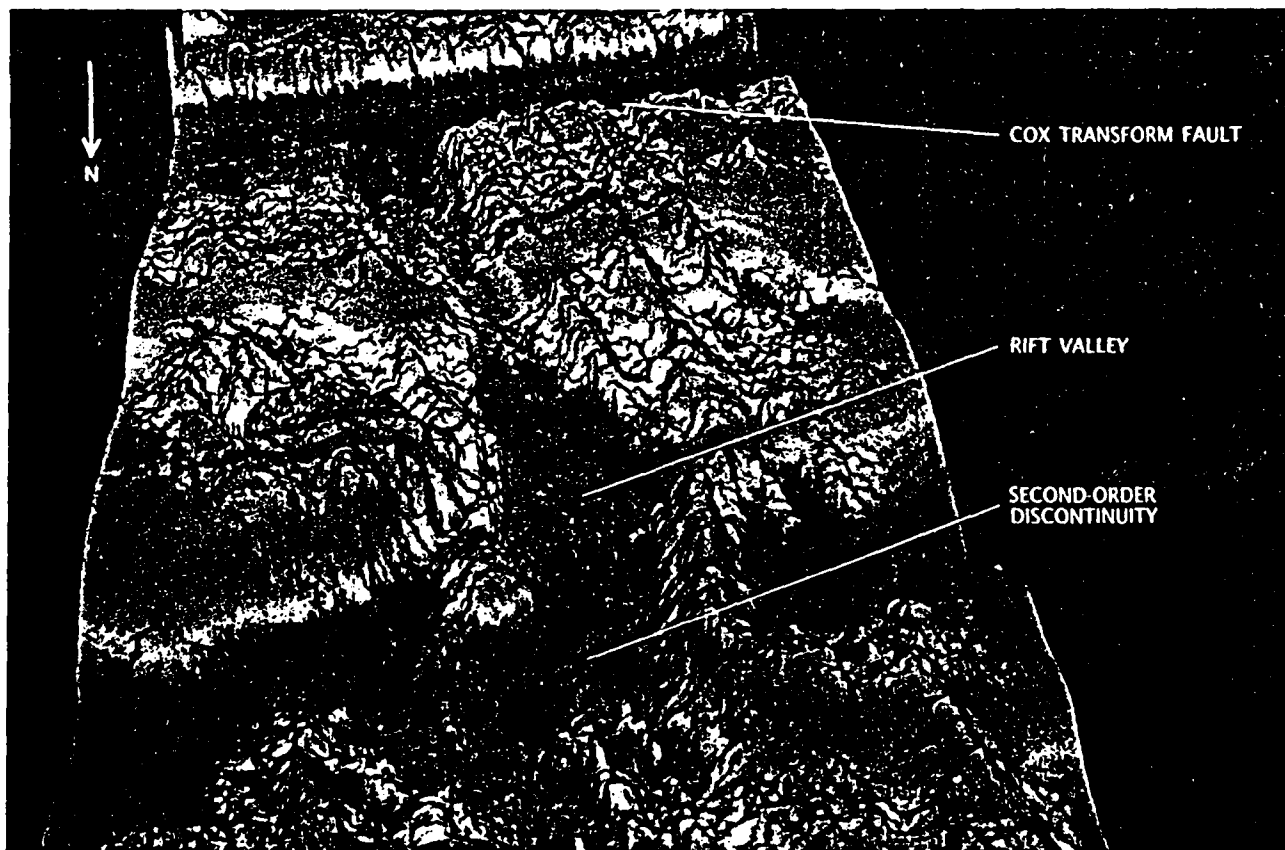
MID-ATLANTIC RIDGE emerges as the South American and African plates pull apart at the "slow" rate of approximately 30 millimeters per year. The axis of the ridge is marked by a two-kilometer-deep rift valley, which is typical of most slow-spreading ridges. The map reveals a 12-kilometer jog of the rift valley, a second-order discontinuity, and also shows a first-order discontinuity called the Cox transform fault. Colors indicate depths of from 1,900 (pink) to 4,200 meters (dark blue).
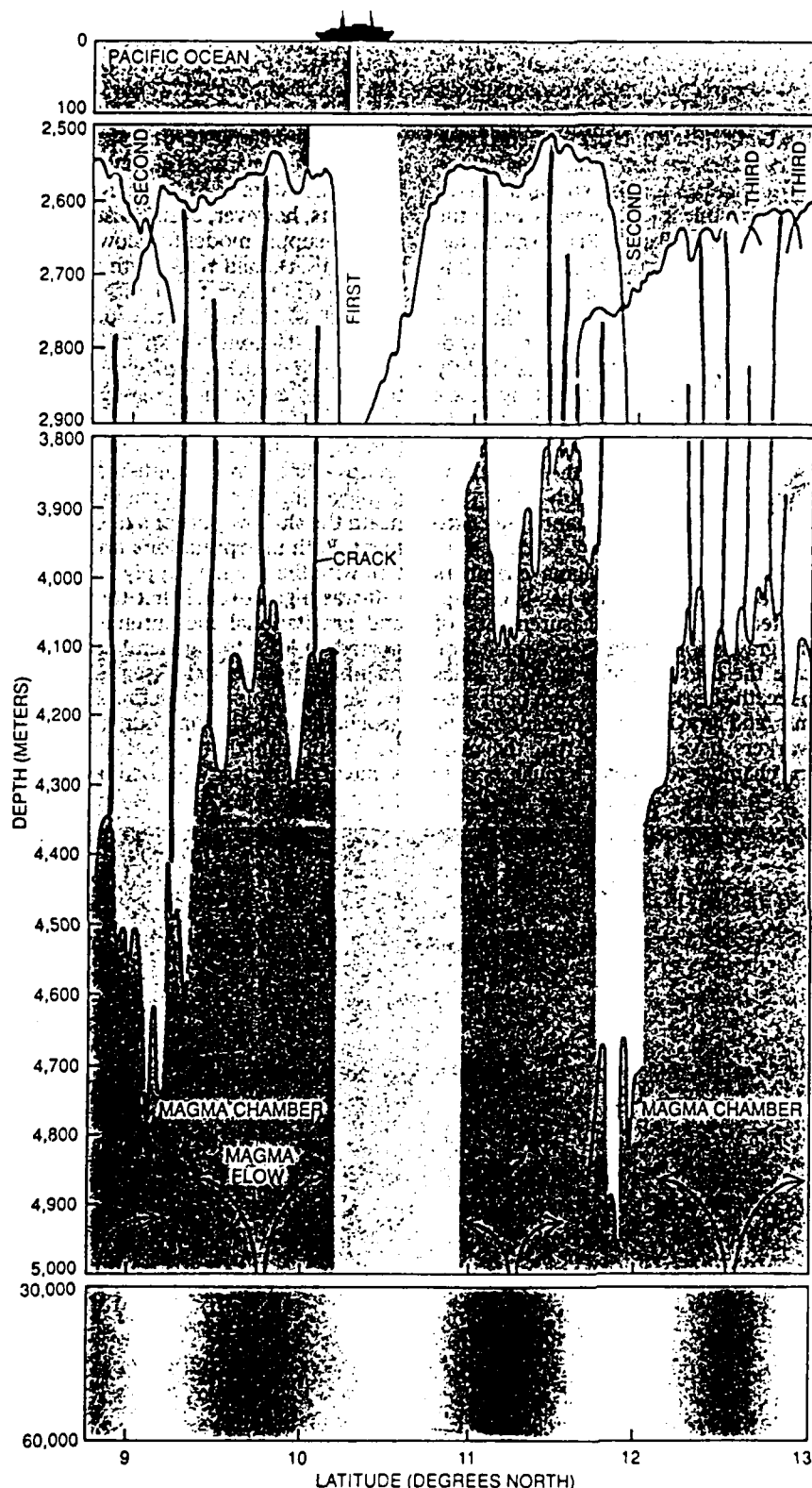
MAGMA seeps up from deep within the mantle to form the East Pacific Rise (shown in cross section along the crest of the ridge). Investigators speculate that partially melted rock from depths of 30,000 to 60,000 meters percolates upward and is produced in greater quantities in some areas (*dark red*) than in others (*light red*). They propose that the molten rock fills and expands magma chambers. Seismic measurements suggest that the tops of the chambers are at the depth indicated by the broken red line. Molten rock ascends from the magma chamber through cracks in the crust and then solidifies or erupts onto the ocean floor. The depth of the ridge (*black line at top*) was determined from sonar measurements. The chamber breaks below discontinuities of order one, two and sometimes three.

be larger, and it remains to be seen if magma actually flows laterally below the ridge axis, but significant evidence has been found to support the model.

Discontinuities

The magma-supply model has been quite successful in accounting for the many different types of discontinuities and segments. Such structures are classified as first, second, third or fourth order according to their size, longevity, geometry and behavior. It has been demonstrated that first-, second- and third-order structures are fundamental components of both fast- and slow-spreading ridges. (The role of fourth-order features remains unsolved.) Because these structures have been investigated in more detail on fast-spreading ridges, we will describe them in that setting first.

The most common type of first-order discontinuity is the transform fault. It appears where rigid plates slide past each other. First-order discontinuities offset the ridge segments by at least 20 kilometers and usually more than 50 kilometers. Hence, most transform faults were large enough to be revealed by early reconnaissance-mapping efforts. These discontinuities typically define segments from 200 to 800 kilometers long.

On the ocean floor, transform faults appear to be narrow, straight bands linking the ends of segments. These bands can be traced in the flanks of a ridge for hundreds to thousands of kilometers [see illustration on page 73]. Such traces indicate that first-order structures persist for millions to tens of millions of years.

A first-order segment can be broken up by several second-order discontinuities that are usually spaced from 50 to 300 kilometers apart. Unlike first-order structures, however, second-order segments are not rigid, and their motion is not concentrated along a narrow fault zone. Second-order discontinuities are complex features characterized by oblique and overlapping structures.

Second-order discontinuities are typically features that resemble the arms of two people who are preparing to shake hands. The arms (ridges) are extended in such a way that the hands (the curved ends of ridges) overlap. The distance between the "hands" varies from one to 20 kilometers. The offset is typically three times shorter than the distance that the ridges overlap. Such a feature is known as an overlapping spreading center [see illustration on opposite page].

When overlapping spreading centers were discovered in 1982, we could not account for many of their characteristics. Why did so many centers have an overlap-to-offset ratio of 3 to 1? What happened to the crust that lies between the overlapping ridges? Why did the ridges create a distinctive curving pattern?

In 1984 David D. Pollard of Stanford University, Jean-Christophe Sempere, then at the University of California at Santa Barbara, and one of us (Macdonald) found that the highly repetitive shape of overlapping spreading centers could be explained by the way cracks develop and propagate along ridges. As tectonic plates are pulled apart, cracks form perpendicular to the direction of tension. In the middle of a segment the direction of stress is usually perpendicular to the ridge axis, so the cracks will lengthen parallel to the ridge. In the region of overlapping segments, however, the direction of stress can vary. As a crack from the middle of a segment begins to grow toward the region of overlap, the crack first deflects away from the region and then hooks toward it [see illustration on next page]. The crack allows magma to erupt onto the ocean floor, and a new ridge tip is formed. But once the cracks overlap by a distance that approaches three times their offset, the crack propagation stalls abruptly. Soon after, a new crack begins to develop behind the first. As the second develops, the first ridge tip is shed off onto the flanks because of plate separation.

Off-Axis Structures

Spreading centers that overlap by more than several kilometers usually leave "wakes" of deformed oceanic crust up to 80 kilometers wide. The ocean floor within such a disturbed region, called a discordant zone, is 100 to 300 meters deeper than the surrounding ocean floor; in like manner, the overlapping spreading centers lie 100 to 300 meters deeper than the shallow, magmatically robust portions of the ridge segments. These features have emerged from maps that several expeditions have made of the flanks of the East Pacific Rise. The maps of the discordant zones also show curved fossil ridge tips 10 to 40 kilometers long, which have been cut off at overlapping spreading centers.

The magma-supply model appears to account for the structure of the overlapping spreading centers. It seems that overlapping spreading centers are at the ends of magma sources and tend to be deprived of magma. If this is true, the crust created at overlapping spreading centers may be up to 50 percent thinner 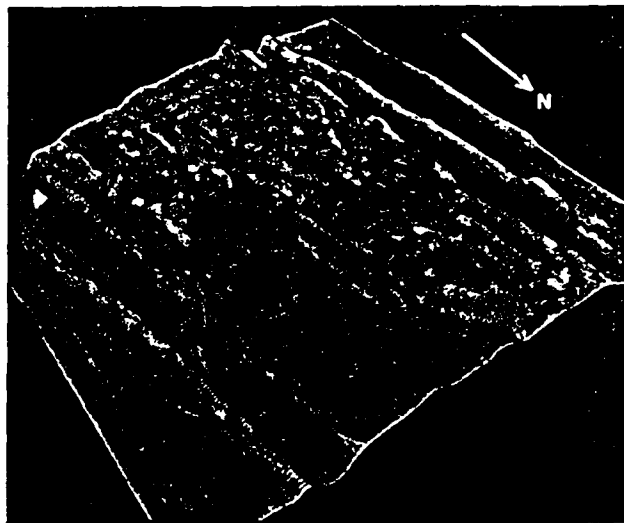than the six-kilometer-thick crust near the centers of each segment. Detailed seismic and gravitational measurements need to be made in these areas to test this idea.

Measurements of the earth's magnetic field at overlapping spreading centers support the idea that such centers occur where the magma supply is low. It turns out that lava that erupts from small magma chambers, which alternately solidify and become replenished, tends to contain more iron-rich minerals in a highly magnetized state. On the other hand, magma chambers large enough to remain molten between episodes of magma replenishment produce lava that is magnetically weak. Because rock near overlapping spreading centers is often much more strongly magnetic than rock elsewhere along the ridge, it seems likely that the centers are fed discontinuously from isolated pockets of magma.

Based on the age of the crust into which the discordant zones extend and on the patterns of off-axis wakes, Laura J. Perram, Suzanne M. Carbotte and Marie-Helene Cormier of the University of California at Santa Barbara have demonstrated that second-order segments persist as discrete entities for up to several million years. The discontinuities may slowly oscillate in position by 10 to 20 kilometers on the ridge or may migrate along the ridge many tens of kilometers at rates of 20 to 100 millimeters per year. A disconti-
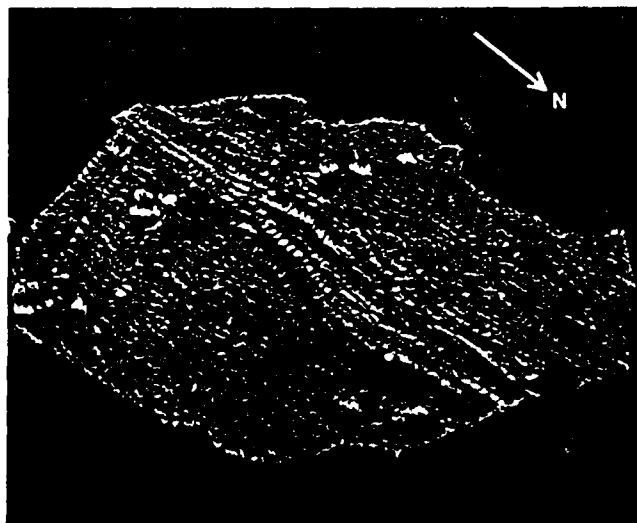
OVERLAPPING SPREADING CENTER, which cuts across the East Pacific Rise near latitude 12 degrees north, was surveyed to determine its topography (left) and magnetization (right). The topographic map shows that the overlapping spreading center offsets the Rise by eight kilometers. Colors indicate depths of from 2,350 (pink) to 3,500 meters (dark blue). The two arms of the discontinuity overlap by 27 kilometers. The arms narrow and deepen near the discontinuity, presumably because the supply of magma to the region is low. The ocean floor near the discontinuity—also known as the wake—is unusually deep and is littered with ridge tips, especially on the west side. It turns out that regions that are not well supplied with magma are highly magnetized. In the map at the right, magnetization decreases in strength from red to yellow regions. The map reveals the wake (red) of the overlapping spreading center. The green-blue troughs were created 700,000 years ago when the earth's magnetic field reversed polarity. The wake shows that the overlapping spreading center emerged about 700,000 years ago, migrated north a short distance and then moved slowly south at 70 millimeters per year. In the past 200,000 years migration to the south has accelerated to 200 millimeters per year.

nuity tends to move in spurts; a ridge segment can lengthen at rates of several hundred millimeters per year but then may retreat and shorten for a time before making the next surge forward. In this way, the ridge tips at a second-order discontinuity appear to be "dueling" as they surge back and forth along the ridge, generally making slow progress in either direction [see illustration below].

Small Overlaps and DEVAL's

Along the East Pacific Rise, third-order discontinuities usually consist of overlapping spreading centers that offset the ridge by less than three kilometers. Segments defined by third-order discontinuities are from 30 to 100 kilometers long. Third-order discontinuities have been shown to correspond with breaks in magma chambers.

The ridge segments defined by third-order discontinuities leave little or no evidence of off-axis wakes. Because they produce little trace in old oceanic crust on the ridge flanks, we can conclude that third-order discontinuities are geologically short-lived. In fact, we estimate that they are younger than 10,000 years—the time it takes a fast-spreading ridge to generate two kilometers of crust.

Fourth-order discontinuities are either subtle bends or tiny offsets less than 500 meters in size. The structures are often called DEVAL's (for slight DEViations in Axial Linearity). DEVAL's are usually spaced from 10 to 40 kilometers apart. A DEVAL may be the manifestation of a single major eruption and therefore may be as young as hundreds to thousands of years old.

DEVAL's are very difficult to detect. They can barely be resolved with sonar

systems such as SeaBeam, and seismic measurements are not much help either. In some cases the magma chamber beneath a DEVAL deepens slightly and, in rare instances, exhibits an apparent break. In most cases the chambers below fourth-order discontinuities are fairly continuous. During the 1982 cruise one of us (Fox) pointed out to the other (Macdonald) that he had found several DEVAL's in the SeaBeam maps. Macdonald then told Fox that he had been staring at the maps too closely on a rolling ship. We soon agreed that we should focus on the larger offsets if we wanted people to believe our ideas.

Indeed, fourth-order segments (the sections of ridge between DEVAL's) were not recognized as distinct and significant features until 1986, when Charles H. Langmuir of the Lamont-Doherty Geological Observatory, John F.
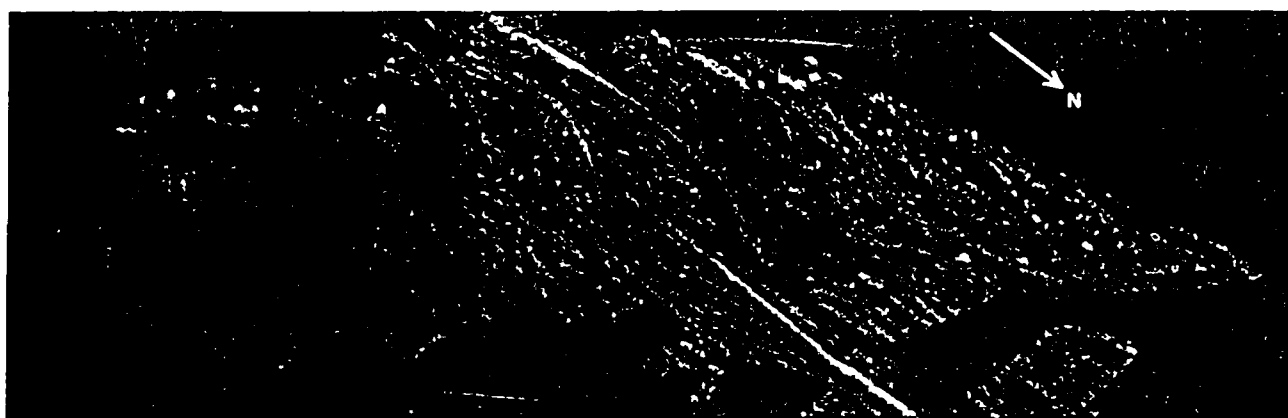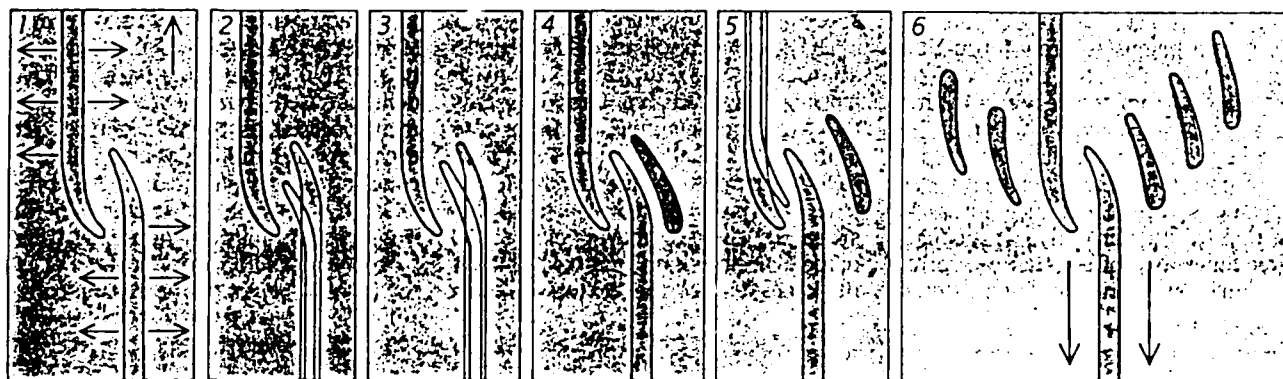
OFF-AXIS FEATURES are generated by an overlapping spreading center, as illustrated in the diagram (top) and the map (bottom). An overlapping spreading center is depicted (1). A crack develops to the south of the eastern ridge tip (2), allowing molten rock to surface and form a new tip. The new tip lengthens until it overlaps the western ridge by three times the distance that separates them (3). As the regions of rock continue to pull apart, the original eastern ridge tip breaks off and migrates away (4). A new western tip begins to form (5). After many episodes of ridge-tip formation and migration (6), the off-axis structures show a net migration to the south. The high-resolution map of a region near 21 degrees south reveals an overlapping spreading center that offsets the East Pacific Rise by 12 kilometers. The discontinuity has had a complex evolution during the past two million years. Migration rates have exceeded 200 millimeters per year as northern and southern ridge tips have surged back and forth, but net migration toward the south has averaged 20 millimeters per year. Numerous abandoned ridge tips within a wake of unusually deep sea floor can be seen on both sides of the overlapping spreading center. Sea-floor structure is disrupted across an 80-kilometer-wide swath adjacent to this discontinuity. Colors indicate depths of from 2,350 (pink) to 2,900 (yellow) to 3,500 meters (dark blue).

Bender of the University of North Carolina at Charlotte and their colleagues analyzed the geochemistry of a 500-kilometer stretch of the East Pacific Rise. The workers collected rock samples from precise sites on the ocean floor to see if structural segmentation could be associated with variations in rock chemistry. They found that the rocks within each fourth-order segment had a similar composition, whereas rocks from other segments had different chemical signatures. Such measurements have documented the fundamental nature of segmentation over a range of scales and have helped to identify many other DEVAL's.

Why do DEVAL's differ in chemical composition? One theory posits that small blockages divide the magma chamber beneath adjacent fourth-order segments. These divisions would prevent the mixing of the magma in the chambers. Yet only a few such breaks have been detected in magma chambers beneath DEVAL's. Another theory suggests that small batches of molten rock from isolated sources in the upper mantle may be injected locally into a magma chamber and may erupt onto the ocean floor before much mixing occurs. This process would create a fourth-order segment with a distinctive rock chemistry. More evidence is needed to confirm or refute these ideas.

We, Carbotte and Nancy R. Grindlay of the University of Rhode Island have documented several kinds of first-, second- and third-order discontinuities at slow-spreading ridges in the South Atlantic. Like the first-order discontinuities on fast-spreading ridges, the slow-spreading counterparts are transform faults. Second-order discontinuities on slow-spreading ridges are defined by a lateral step of the rift valley or by a deep oblique basin along which the offset rift valleys are linked. The second-order discontinuities persist for millions of years—longer on average than second-order discontinuities on fast-spreading centers. Second-order discontinuities on slow-spreading centers also migrate more slowly along the ridge axis than their fast-spreading counterparts. Third-order discontinuities at slow-spreading centers are small offsets in long volcanic chains within the rift valley floor, whereas fourth-order discontinuities may be small gaps between volcanoes.

Aquatic Life and Segmentation

Oceanographers, tectonicists and geochemists have just begun to understand some of the implications of segmentation for both slow- and fast-
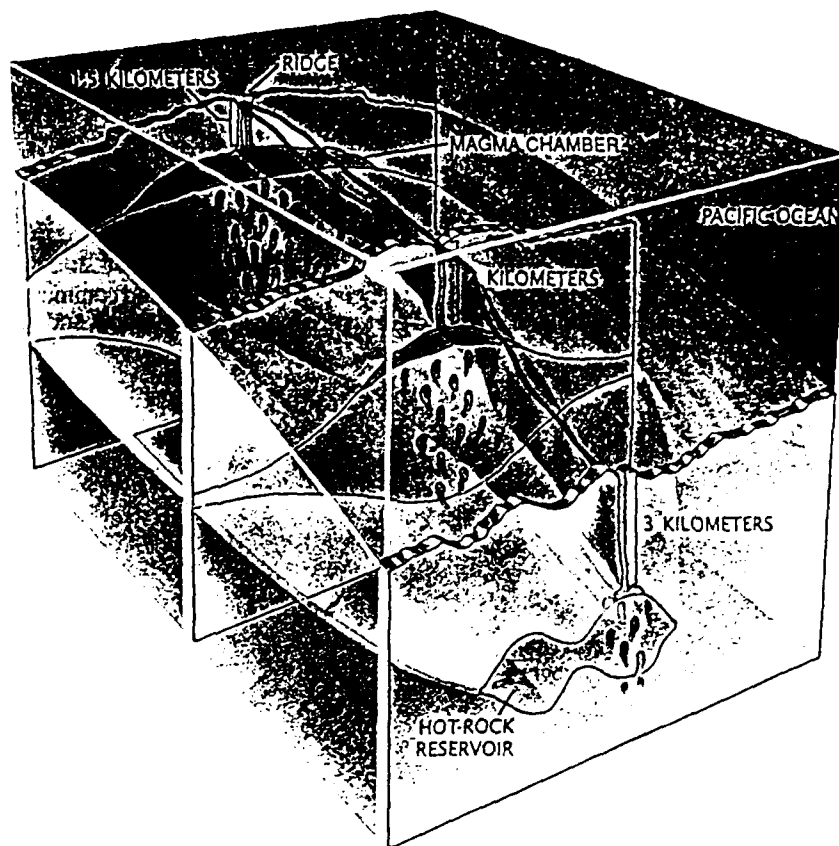
MAGMA CHAMBER is thought to extend below fast-spreading ridges. The magma chamber is a lens of mostly molten rock. The chamber sits atop a reservoir of partially melted rock. The chamber and reservoir are small and poorly supplied with molten rock near a discontinuity (*deep region in foreground*). Yet they can be larger and well supplied at a distance away from the discontinuity (*background*).

spreading ridges. We have found clear examples of first-, second-, third- and fourth-order structures and everything in between. Do segments evolve from fourth through first order and back again? We know that segmentation has been a fundamental process for at least 100 million years. Has segmentation played a role over a much longer period? Investigators have studied exotic faunal communities that flourish near hot springs on the Mid-Ocean Ridge. Can the survival and migration of these communities be linked to the longevity of a given segment?

These questions will be the focus of research for a program called the Ridge Interdisciplinary Global Experiments (RIDGE). Among the many goals of the program are to map the axis and flanks of the entire Mid-Ocean Ridge and to generate more detailed images of off-axis features. Even today geologists and oceanographers have mapped less than 5 percent of the sea floor. More than half of the earth's crust remains to be explored.

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